Closing the loop between food, energy, and waste: A review of energy conversion configurations to support Hawai‘i’s transitions to a circular agro-economy

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Abstract
Soil amendments and fertilizers for agricultural production of food crops can be enhanced by anaerobic digestion (AD; biological degradation of natural materials such as plant biomass or manure into digestate) and pyrolysis (PY; a process of thermophilic decomposition into biochar). Digestate and biochar can improve soil organic matter, modulate pH levels, increase nutrient mineralization and availability, and establish optimal conditions for soil microbial populations. Soil amendments produced by AD and PY contribute to a circular agro-economy that maximizes resource utilization, recovery, and regeneration by directly and indirectly displacing fossil fuel production/consumption, thus contributing to climate change mitigation. A literature review was conducted to determine if AD and PY produced separately (AD/PY) or cogenerated (AD+PY, where the digestate serves as the feedstock for pyrolysis producing pyrochar) would provide positive outcomes within a circular agro-economy. PY may increase efficiency properties of independent AD systems. The application of pyrochar improved fertilizer ratios (1.5:1.5:5.9%), water holding capacity (10-15%), and cation exchange capacity (4-17%), thus improving soil structure, tilth, and nutrient uptake in plants. During the processing of biochar, ammonia toxicity can be prevented by approximately 71% and increase energy output, removes contaminants in soil, and sequesters atmospheric carbon. The catalytic cogeneration of digestate, biochar, and pyrochar uses less energy compared to intensive, high input agriculture and can produce up to a net 42% increase in electricity production. Optimized agronomic use of digestate and biochars should consider direct impact assessments to crop yields and offsets for well-informed management strategies.

Key words: anaerobic digestion; pyrolysis; resource recovery; natural resource management; soil amendments; sustainable agriculture; closed-loop agriculture.

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Section 1. Motivation

A prominent disconnect exists between humans and their environment (Brevik et al 2019; Nieder et al 2018; Sokolov et al 2010; Goldhaber et al 2006), particularly in urban populations (Brevik &Sauer 2015), and is conspicuously reflected in the ways human systems extract, produce, and dispose of natural resources. This linear, and retrogressive flow of materials is a particular concern for island territories because of the limited number of natural resources available to sustain both natural and human ecosystems. In Hawai'i, Native Hawaiians recognize the significance of a healthy environment to support human communities, and that the two are intrinsically connected (Kana'iaupuni & Malone 2006; Kapa-Oliveira 2014; Kurashima et al 2019).

Agro-ecosystems are dependent upon soil health and quality (Addiscott 1995). Soil behaves as a medium for biogeochemical transformations and is comprised of mineral, gaseous, liquid, and biological components (Nieder et al 2018), supporting almost 82% of the world's population (Sarkar et al 2020). Humans fundamentally rely on soil health to efficiently and sustainably regenerate resources to increase human quality of life, and the environment. A first step towards a sustainable agro-ecosystem is to recognize that how humans manage waste and utilize resources has direct impacts on, and are part of, the natural cyclic processes of the environment. This reciprocal and continuous exchange between humans and their environment is the essence of closed-loop agricultural systems that preserve nutrient, carbon, and water cycles that allow the soil to sustain itself.

This disconnect between people and soil makes sustainable solutions to waste, food, and environmental problems challenging. However, efforts to transition to more functional and regenerative circular agro-economy are underway in Hawai'i, and elsewhere globally, and suggest a need for better understanding of continuous energy conversion technologies. Anaerobic digestion (AD; conversion of natural materials into digestate through microbial decomposition) and pyrolysis (PY; conversion of natural materials at high temperatures to produce biochar) are two regenerative technologies that may provide a promising solution to these problems. The application of digestate and biochar to agricultural lands as a locally produced soil amendment or fertilizer has the potential to improve the energetic capacity for soil to recycle nutrients back into the environment, thus providing a long-term ability to sustain food systems and stabilize the environment (Muscolo et al 2017; Pawlowski et al 2018; Tilman et al 2002).

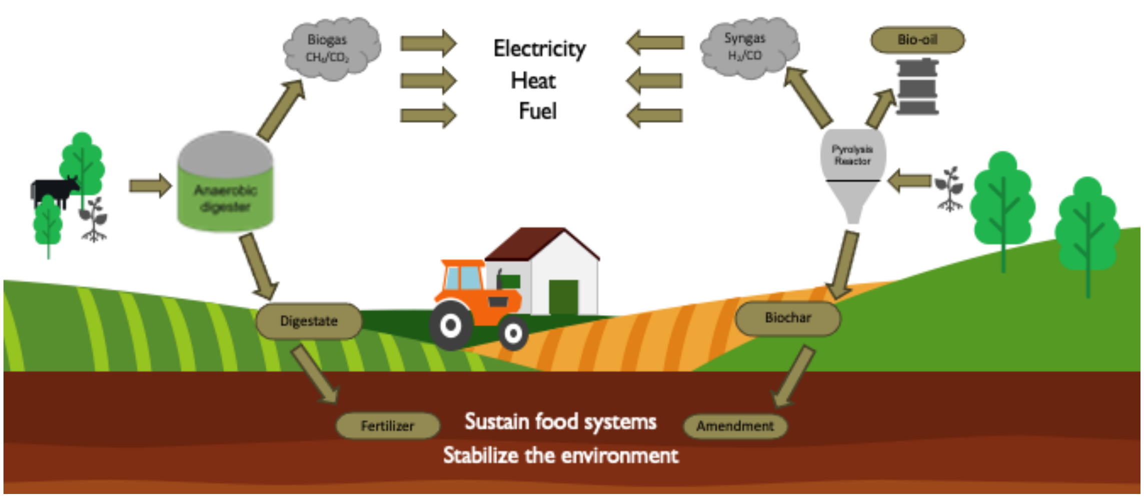

Figure 1. Sustainable energy and nutrient recovery from agricultural residues by coupling anaerobic digestion and pyrolysis.

Section 2. Background

Local Food, Waste, and Energy Targets and Central Problem(s)

The State of Hawai‘i developed the Aloha+ Challenge to identify locally and culturally appropriate goals, metrics and indicators to track Hawai‘i's progress toward achieving its sustainable development goals (Governors Dashboard 2019). AD/PY resource recovery systems would support many of these goals and comply with SB559 which requires the state to expand strategies and mechanisms to reduce greenhouse gas emissions (Hawaii State Legislature 2019). Hawai‘i also enacted three additional bills in 2018 that aim to "*reduce the state's carbon emissions progressively, until becoming completely carbon neutral by 2045*" and increase the use of organic amendments in Hawaii to help improve soil health (Chevalier 2018).

At the same time, the state is struggling to meet local food demands (La Croix & Mak 2021; Land Use Division, 2021). Currently, only 11.6% of available food for consumption in Hawai‘i is sourced from local production (Loke and Leung 2013), despite 45% of terrestrial land being designated for agricultural purposes (Land Use Division 2021). In 2016, Hawai'i pledged to double local food production, yet efforts to develop diversified solutions to improve the 41% of agricultural land that remains fallow (Kurashima et al 2019) have had limited success (Land Use Division 2021).

Hawai‘i also generates roughly three million tons of waste annually, 80% goes directly to landfills and 60% of that is biodegradable (Department of Environmental Services; Gershman et al 2009). Landfills on every island are expected to reach capacity soon (Gershman 2009). Rather than expanding landfills, counties could invest in infrastructure that would enable local farmers to play a role in waste diversion to improve the quality of agriculture land and produce a potentially self-sustaining energy source. H-power is currently Hawai‘i's only waste to energy facility and provides 4-10% of O‘ahu's daily energy supply (Young 2014). However, 84% of the primary energy supply in Hawai‘i is still imported fossil fuels (EIA 2020), and the Environmental Protection Agency recently revealed that waste incineration accounts for roughly 14.9 million tons of annual CO_2 emissions (EPA 2019). This conflicts with the state's carbon emission reduction goals and suggests diversified solutions to waste management and energy supply, in addition to local food production, are also needed.

Existing literature on AD for agriculture use is primarily focused on the analysis of the digestate byproduct (Kouřimská et al 2012; Chiew et al 2015; Koszel and Lorencowicz 2015), with little evaluation about how the application of digestate to soils affect soil ecosystem functions and environmental health (Muscolo et al 2017). Furthermore, optimization of the biogas production from AD in terms of process stability, higher methane yields, and inhibition problems need further investigation (Mumme et al 2014; Ward et al 2008). AD/PY, with PY preceding or succeeding AD, may be a sustainable approach to conserving soil fertility and promoting the closure of natural nutrient cycles (Arthurson 2009; Gutser et al 2005; Monlau et al 2016).

Section 3. Objective

The objective of this project was to review potential benefits that can be obtained from the co-use of AD and PY with agriculture residues as primary feedstock. Specifically, this project investigated various configurations of AD/PY that could help Hawai‘i transition to a sustainable circular agro-economy. I focused on configurations that would specifically have potential to improve local food production through improved soil conditions, improve environmental conditions through reduced climate emissions, and provide a viable source of renewable energy. The soil, environment, and energy efficiency contributions of AD/PY reviewed in this report assume that by prioritizing efforts to ameliorate and preserve soil health and quality, the state of Hawai'i can more realistically achieve its goal to increase local food production and diversify the agriculture economy.

Section 4. Approach

First, I conducted a comprehensive literature using the University of Hawai'i's online library database and explored publications that contained the key words "anaerobic digestion" and "pyrolysis" in connection with agriculture benefits specifically characterized by "soil health", "circular economy", "waste to energy", and "environmental health". The available peer reviewed scientific literature on AD and PY varied considerably, thus I analyzed potential agricultural, environmental, and economic benefits that would be applicable to Hawai'i. Applicability was determined by the waste product that was used as feedstock, and whether this feedstock is readily available and accessible in Hawai'i.

Next, two specific case studies that used agriculture wastes as feedstock were selected from the literature to comprehensively examine the measurable improvements to the soil amendment byproduct and energy output. The case studies also compare two different processing pathways including AD → PY, and PY → AD. Environmental improvements coincide with soil health (indicated by the enhanced soil amendment product) and are determined by biological, physical, and chemical parameters that are appropriate for Hawai'i's diverse climate regions and production systems (Chapin 1996; Harden 2018; Hubanks et al 2018; Hubanks 2019). Potential energy improvements in each study were determined by outputs in biogas and/or syngas and bio-oil production. Finally, a proposed configuration of AD/PY based on the findings of the case studies and potential benefits from the literature is discussed with a consideration of possible revenue streams, thus economic improvements.

Section 5. Results

Summary of Potential Benefits Examined in Scientific Literature

Potential benefits of utilizing AD/PY that were reviewed in the literature include the potential to improve agriculture systems and long-term net benefits to soil (Colombani et al 2017; Gutser et al 2005; Lošák et al 2020; Lukehurst et al 2010; Möller 2015; Yu et al 2018), potential to displace fossil-fuel based agriculture inputs (Crombie et al 2015; Lukehurst et al 2010), such as chemical fertilizers, and potential to mitigate climate change and provide a viable source of renewable energy (Jiang et al 2019; Pandey et al 2019; Solarte-Toro et al 2018; Surendra et al 2014). There is also potential to expand the use of these systems for integrated waste management systems (Abraham et al 2021; Bichi et al 2020; Chen et al 2017; Cao & Pawlowski 2012; Giwa et al 2019), cross-sector resource management tools, which researchers refer to as "Industrial Symbiosis" (Abraham et al 2021; Giwa et al 2019), and can also benefit other conservation practices such as invasive and diseased plant species management (Inyang et al 2010; Van

Meerbeek et al 2015; Pitts 2019; Solarte-Toro et al 2018). The continuous digestion of biodegradable wastes through AD/PY is a holistic approach to efficiently recover waste and improve feedback loops between the environment, food, and fuel (Feasta 2016; Gomiero et al 2008; Sarkar et al 2020).

Case Studies on Soil, Environment, and Energy Improvements from AD/PY

Case Study 1. *Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management: Comparison between solid-digestate and its derived pyrochar as soil amendment* (Monlau et al 2016).

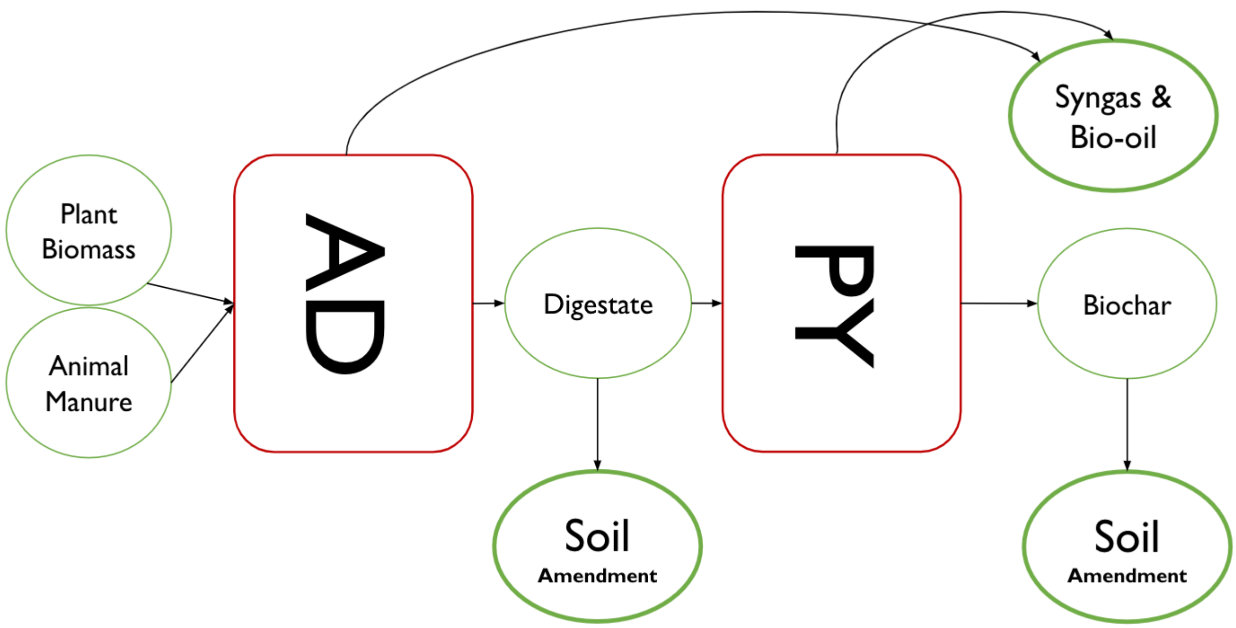

Figure 2. Digestate produced from the AD of agriculture waste (mixture of animal slurry and plant biomass) as feedstocks can be supplied to PY to enhance the soil amendment quality. The resulting biochar applied directly to soil with digestate has greater remediation potential than the independent application of digestate.

Overview: Researchers in Foggia, Italy compared the impact of PY on two digestate samples produced from AD on two different farms. On the first farm, feedstocks included animal manure and a high lignocellulosic mix of plant biomass and crop residues (9% groats, 29% olive oil cake, 57% silage of triticale and 5% chicken manure). A similar feedstock mixture on the second farm comprised animal manure and crop residues (43% animal sewage, 20% cow manure, 25% maize and triticale silages and 12% cereal bran). Both digestate samples (7.1 and 6.7 tons, respectively) were analyzed for biogeochemical parameters and then were processed through PY. The PY process on both digestates each produced a biochar yield of 30% which were then analyzed for the same parameters as the digestate.

Improvements to Soil Amendment and Energy Output

The findings from this study showed that the solid digestate has high biological stability, relatively high organic matter content, and nutrients such as N and P, indicating a viable replacement for imported soil amendments and fertilizers. The improvements of the fertilizer ratios (1.5:1.5:5.9%), water holding capacity (10-15%), and cation exchange capacity (4-17%), indicate a potential to improve soil structure, tilth, and nutrient uptake in plants when applied to soil. The liquid fraction resulted in rich ammonia (NH_3) concentrations, indicating an analogous fertilizer for N mineralization. However, when N already exists in high quantities in soil, there risks a chance that plants may take up excess N leading to cellular damage and impacting plant growth (Nkoa 2014). The liquid digestate can be applied directly to soil, however, close monitoring of NH_3 levels in the soil after each application is recommended to prevent ammonia toxicity. The co-application of biochar could mitigate the concern of ammonia toxicity and may improve the energy output in the digester which is also inhibited by excess N (Zhang et al 2018).

Regarding energy output, the subsequent PY step produced additional energy byproducts in the form of bio-oil (51% and 56% for the first and second farm, respectively) and syngas (15% and 10%, respectively). Bio-oil can only be used directly as fuel if it contains less than 30% water content (Hossain et al 2016; Neumann et al 2015). In this case, the bio-oil revealed a water content of 45%, indicating it needs to be treated with an additional processing step before it can be used for heat and electricity (Hossain et al 2016; Neumann et al 2015). However, the total net energy gain of 42% using the same process in an earlier study (Monlau et al 2015) indicates pyrolysis could still improve the renewable energy output, and still obtain a high-quality soil amendment as seen in this study. Another option of AD/PY integration is to begin with the PY of feedstock to obtain a biochar that is then fed to AD. The next study showed that the alternative pathway, PY→ AD, may provide a soil amendment byproduct with even more long-term benefits to soil and energy through improved efficiency of the AD process.

Case Study 2. *Use of biochar in anaerobic digestion* (Mumme et al 2014).

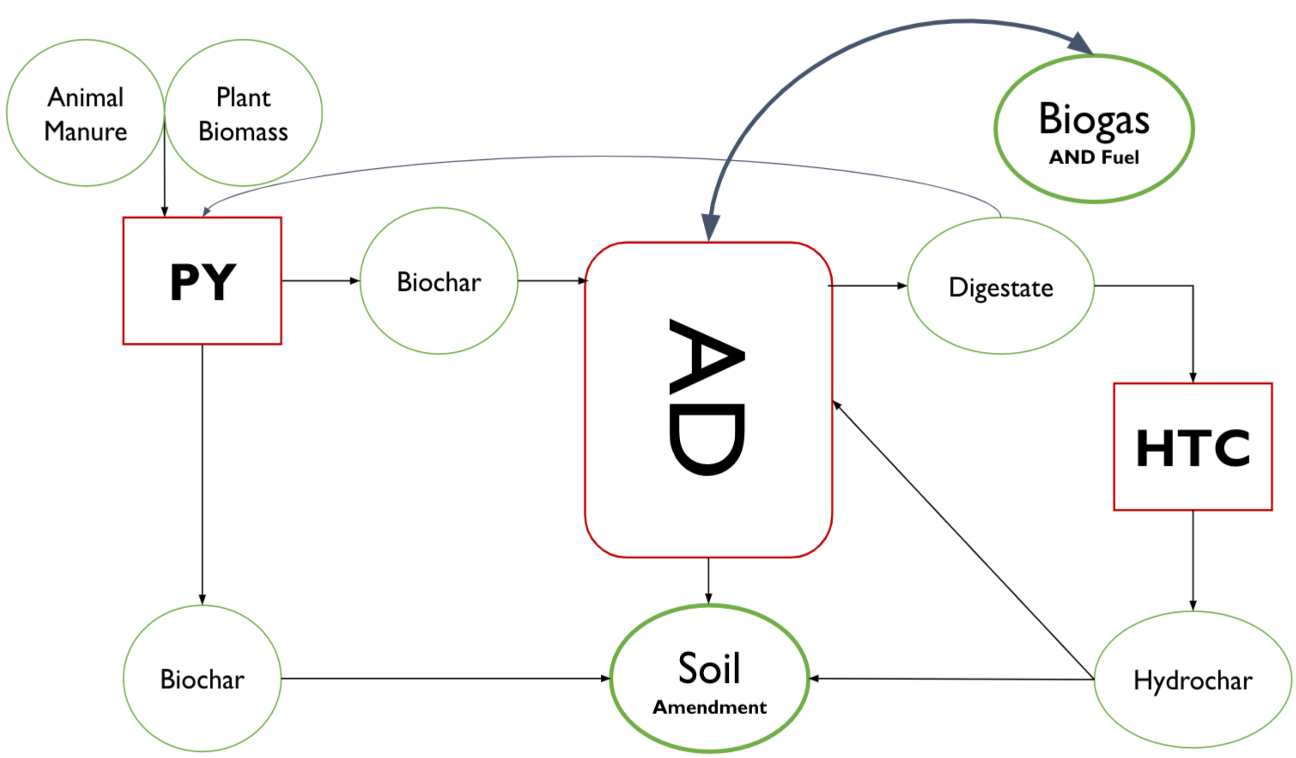

Figure 3. The properties and behaviors of two different types of biochar in AD to enhance biogas production and ammonia inhibition were examined and compared for their ability to improve the stability and efficiency of stand-alone digesters. A depiction of the AD/PY system proposed by Jan Mumme et al. shows the co-processing of feedstocks through PY and AD, and further optimized with hydrothermal carbonization (HTC) of the digestate.

Overview: In this study, researchers analyzed two types of biochars to optimize the AD processing step: 1) pyrochar derived from the thermal decomposition of digestate from the AD of a 1:2 (v/v) mixture of paper sludge and wheat husks; and 2) hydrochar derived from the hydrothermal carbonization of digestate from the AD of wheat straw. The difference between the two PY processes (thermal and hydrothermal) is characterized by water content, 30% and 90% respectively.

Improvements to Soil Amendment, Energy output, and Inhibition Problems

Chemical analysis of the pyrochar revealed a dry matter content (54.7%) comprising ash (39.2%), C (51.5%), N (1.55%), and H (1.24%), compared to a 99.8% dry matter content in the hydrochar comprising 7.8%, 65.3%, 1.44%, and 3.24% of ash, C, N, and H, respectively. The structure of the pyrochar also showed high potential to improve soil microbial processes because of the resulting biofilms created on the particle surface. While the higher organic matter content in the hydrochar was improved, its significantly lower pH of 4.8, compared to 9.8 in the pyrochar, is not suitable for soil application.

However, in this study, the researchers compared the ability of pyrochar and hydrochar to reduce high N levels in the anaerobic digester to improve energy output and found that the hydrochar removed much more N than the pyrochar. Therefore, while hydrochar is not a suitable soil amendment, it could improve inhibition problems in AD to improve energy yields (Phuttaro et al 2019). Biogas yields from the hydrochar supplied back to AD increased by 32%, whereas the pyrochar showed no clear improvements. Other researchers show that energy can increase even more significantly with the co-digestion of manures, which have high methane yields (between 148-473 ml/g) (Ward et al 2008). Therefore, special attention should be given to feedstock characterization.

Section 6. Discussion

Agriculture and Energy benefits of AD/PY

Continuous co-digestion of plant and animal residues as feedstock for AD/PY can increase soil amendment production and quality and improve net energy gains and AD efficiency. The increased capacity to mitigate high N levels in AD and improve the plant-available nitrogen, suggests using digestate and biochar for soil amendment and fertilization provides greater potentiality for increased soil, environmental, and energy benefits. The concatenate application of digestate, biochar directly to soil can improve soil organic matter, modulate pH levels, increase nutrient availability, and establish optimal conditions for soil microbial populations, which are crucial to maintain biogeochemical functions that support balanced and healthy terrestrial ecosystems.

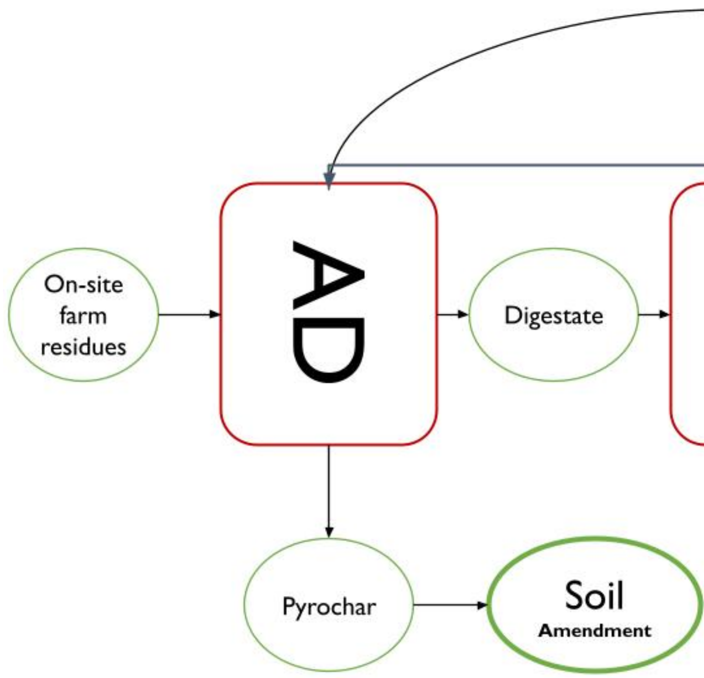

Figure 4. A proposed configuration that depicts on-site farm residues first processed by AD to capture the biogas byproduct, and then the digestate is supplied to PY to produce biochar. Fractions of the biochar can be immediately applied to soils to increase soil organic carbon, sequester excess carbon from the atmosphere, and stabilize acidic soil conditions. The remaining fraction can be supplied back to the digester to obtain pyrochar to enhance the soil amendment byproduct with greater long-term net benefits to the soil through enhanced soil microbial activity and improved mineralization of nutrients. The additional energy output from the PY step also produces bio-oil and syngas that can be used for electricity, heat, and fuel.

Agro-economic improvements

AD/PY has potential to provide renewable energy for Hawaiʻi and increase food security. Without the need for conventional input, and a decrease in farmers' operational costs with the utilization of self-producing energy, farming productions could be less expensive to operate and therefore could potentially lower the costs of local food. In addition to soil remediation, increased crop yields and energy production can also provide an additional source of income for farmers. For example, farmers can sell excess energy products to statewide electricity and fuel distributors. This is a major incentive for farmers in Hawaiʻi to adopt these resource recovery and conversion systems, however, more investigation is required. Farm use of AD/PY can provide models to be considered by other operations on the state and county levels, including the potential to replace landfills by diverting larger waste streams.

Future Research

Further feasibility research is needed to determine whether these bioenergy conversion systems in Hawaiʻi are economically practical. For instance, a benefit-cost analysis would measure the monetary and non-monetary benefits and costs of operating these systems on a farm level, and on an island-wide or state-wide level. A local field study would help determine specific application rates of the byproducts to soil, which may vary from farm-to-farm depending on the soil conditions. A field study would also help inform which readily and available feedstocks on a farm would produce the greatest energy yields and best soil amendment quality. On a larger scale, an inter-island waste life cycle analysis would be useful to determine how to divert waste materials to their highest and best use. For instance, maybe some of the waste is best for incineration, and maybe others are best in an AD/PY system. Finally, an initial investment needs to be quantified due to the additional infrastructure needed to obtain the AD/PY configuration, and the long-term benefits from improved soil health parameters, i.e., improved crop yields, and ability to displace fossil fuels and sequester excess carbon from the atmosphere, i.e., environmental improvements, that are expected.

Section 8. Conclusion

Improved resource recovery (i.e., regeneration) from AD/PY and the resulting preserved nutrient and carbon levels within the soil can remediate impoverished soil conditions, generate energy and fuel for long-term management and recycle nutrients back into ‘āina (that which feeds us), suggesting a promising soil remediation and land management strategy for local farmers. PY can improve the overall efficiency of the AD system and obtains extra-energy benefits. The continuous processing of renewable resources through this regenerative system has potential to support agriculture needs to grow crops and improve the health and life of the soil so that it can sustain the community in pursuit of achieving reduced climate emissions. This regenerative waste-conversion system encourages a paradigm shift of consciousness in the way we perceive and utilize waste, contributes to the development of progressive solutions to improve ecosystem function and environmental health, and can enhance agricultural systems for local food production in Hawai‘i.

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